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MOLECULAR ION PHOTODISSOCIATION INJECTION*

R. Arnold, R. Burke, Y. Cho, R. Cutler
S. Fenster and R. Martin
Argonne National Laboratory
Argonne, Illinois 60439

Summary

A new technique for injecting an ion beam into a storage ring is presented. The idea arose in connection with high energy ion beam fusion where a large degree of transverse stacking in both planes would otherwise be necessary. The method involves accelerating a molecular ion such as HI^+ but storing the atomic ion I^+ by photodissociating the molecule at injection. The irreversibility of the reaction $\gamma + HI^+ \rightarrow H^0 + I^+$ renders irrelevant Liouville's theorem, which, with standard injection, would prevent new beam from being injected into the same space as already circulating beam. Xenon flashlamp and ruby laser systems for accomplishing molecular ion dissociation (MID) are described.

Some high energy ion beam fusion system alternatives require a large degree of transverse beam stacking. In ten megajoule cases it is not uncommon to need five hundred turns of injection into storage rings, which implies stacking in both planes to a degree hitherto untried. Although methods are likely to be devised to achieve this, it seems worthwhile at this time to consider an injection technique, called molecular ion dissociation (MID), which avoids the consequence of Liouville's theorem that the phase space volume is a constant of the motion for elastic interactions. The principle is the same as that of the currently operational charge exchange injection, where an inelastic reaction allows new beam to be injected into the same space as beam already circulating in a ring.

Consider a storage ring to be filled with singly-charged heavy ions, say iodine (I^+). The technique consists in accelerating in the linac or synchrotron feeding the ring the molecular ion singly-charged hydrogen iodide (HI^+), and photodissociating

$$\gamma + HI^+ \rightarrow H^0 + I^+$$

at injection with flashlamp or laser light. The ring captures I^+ and rejects hydrogen atoms. The mass change (about 1%) involved eliminates the reversibility condition necessary for the relevance of Liouville's theorem.

The choice of HI^+ is not unique, but there do not seem to be very many candidates. A heavy ion is required in fusion applications to reduce 1) the range of the ion in the pellet and 2) the current necessary to achieve 10 MJ stored energy; the dissociation energy must be a few eV to permit flashlamp or laser dissociation; the molecular ion must not come apart during linac or synchrotron acceleration; the cross section for dissociation must be reasonably large ($\sigma \sim 10^{-21}$ m^2); the cross section for undesired reactions (such as $\gamma + I^+ \rightarrow I^{++}$) should be small ($\sigma \sim 10^{-25}$m^2); one must be able to make a 50 mA source.

Given HI^+ the reaction would mainly proceed via the two-step process of photoexcitation to a band B of excited states[1] above the ground state followed by dissociation. Actually, the source is likely to populate both a $^2\Pi_{2/3}$ and a $^2\Pi_{1/2}$ state about equally; these are separated by spin orbit splitting by about .6eV. A photon energy of about 3.6 eV is necessary to get the populations of both states into B.[1] A xenon flashlamp will supply the right wavelength; a ruby laser will work if doppler shifted by the beam velocity. The best system for each is somewhat different.

If MID is to be carried out by laser light, a possible arrangement is shown in fig. 1. The HI^+ beam is injected at the septum to join the I^+ circulating beam. A ring magnet forces HI^+ and I^+ to follow a common path through quadrupoles into a dissociation region. The region is 1 m. long and the beam diameter is 2 mm at minimum. The laser light is incident longitudinally in a direction opposite to the ion beam motion, is emittance matched, and dissociates some fraction of the HI^+ as well as further ionizing I^+. The latter reaction loses useful beam. The fraction of HI^+ that has not been dissociated is sent through a recirculating ring and returned to the dissociation region; this process is repeated r times. During each pass the number of HI^+ is multiplied by a factor $\frac{f}{re}$. It is necessary to take $r = 50$ because the beam pulse time is about 20 μs. while a natural laser burst time is near 1 ms.

High power lasers must be used. A ruby laser ($\lambda = 6943$ Å) has energy 1.78 eV (2.85×10^{-19} joules) per photon, which is too low. However, since the laser is aimed so that photons and ions have opposite directions, a Doppler factor

$$\gamma(1+\beta) = \sqrt{\frac{1+\beta}{1-\beta}}$$

is gained. To reach

$$\sqrt{\frac{1+\beta}{1-\beta}} \geq \frac{3.6}{1.78}$$

requires

$$\beta \geq .6 \qquad \gamma \geq 1.25$$

which means the kinetic energy of the HI^+ beam must be at least

$$E_1 \geq 30 \text{ GeV}.$$

In our example E_1 is 80. GeV.

To estimate the required laser parameters we use the notation of Table I. To calculate E_ℓ one notes that the ratio of occupied volume to illuminated volume is proportional to

$$\frac{\ell}{A}$$

where ℓ is the length of the interaction region and A is the beam area. If z is the longitudinal distance and Θ is the divergence angle, the beam radius is given by

$$r(z) = \sqrt{a^2 + \Theta^2 z^2}$$

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where a is the waist. For $A = \pi r^2$ dependent on z the above is replaced by

$$\int \frac{dz}{A} \quad ,$$

whence $\frac{\ell}{A}$ gets replaced by $\frac{1}{\varepsilon}$, where ε is the emittance $\varepsilon = a\theta$. This yields

$$E_\ell = \frac{\varepsilon L f}{\sigma} E_d \quad , \qquad P = \frac{v}{L} E_\ell \quad .$$

See Table I. At present a ruby laser supplying 100 J. in 1 ms. at .2 Hz. and 6 mrad. - cm. is available. This repetition rate may be increased to 5 Hz. by using a bank of 25 lasers. Add a factor of 100 to compute the power supply.

The flashlamp would consist of a tube several meters long running parallel to the (transparent) beam pipe. An elliptic reflector with beam and lamp located at its foci would concentrate the light. Parameters are given in Table I. The energy per flash equals the product of fE_d by the ratio of the illuminated area to the occupied area. The illuminated area is

$$A_I = 2\pi aL$$

while the occupied area is (N = no. of ions)

$$A_o = N\sigma \quad .$$

This gives

$$E_f = \frac{2\pi aL}{\sigma} \cdot fE_D$$

in a time $\frac{L}{v}$. A factor of 10 in energy will be needed for losses in the optical system. At present flashlamps will provide 2000 J. in 20. μs. at .2 Hz, so 1000 lamps would be needed.

Conclusions

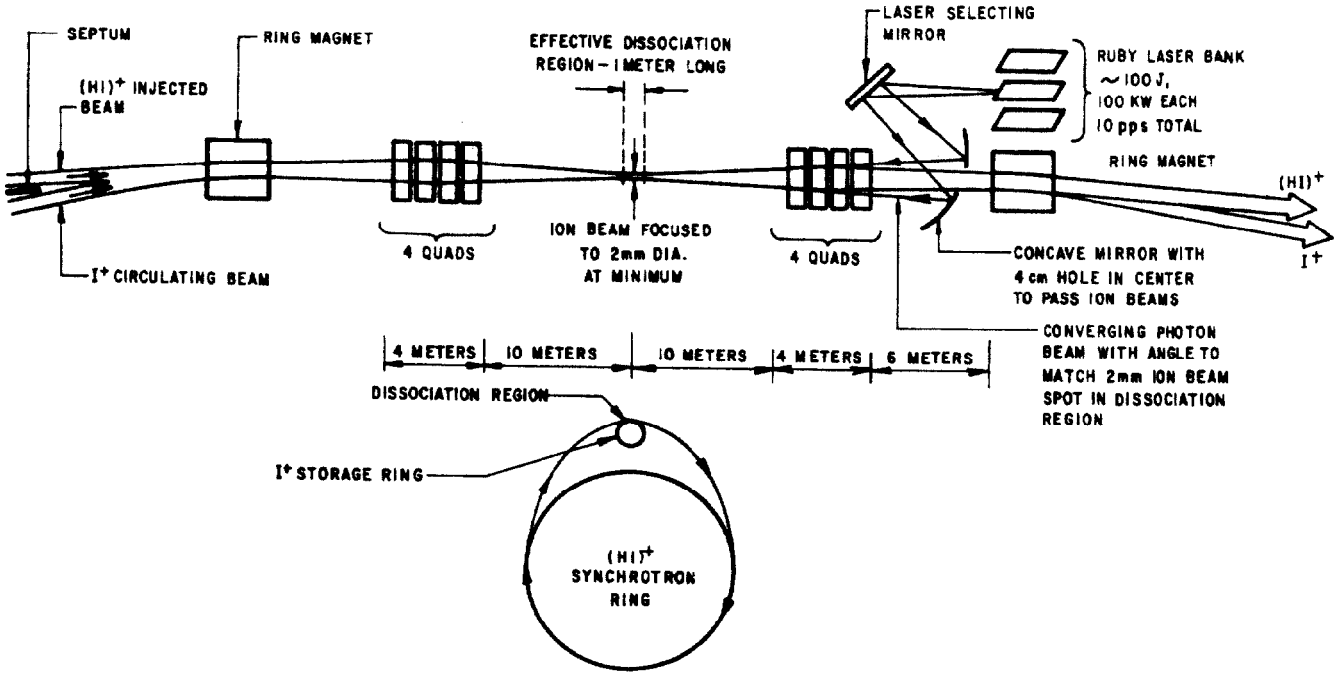
MID requires a rather complicated but probably feasible optical system. Commercially available hardware will not be satisfactory so special designs will be required. The energy needed per pellet microexplosion is very high. For the flashlamp it comes to .04 times the energy carried by the beam. Several hundred flashlamps will be needed. If the repetition rate is between 2 Hz and 10 Hz there will be a severe heat dissipation problem. Too much water cooling may absorb light energy before it reaches the beam. There is also danger of explosions. Use of lasers gives a small energy requirement per cycle at the dissociation region, but to get a sufficient repetition rate a bank may be necessary to reduce the duty cycle of each laser. A special ring may be needed for the recirculation process. Advantages of MID are: the emittance of the source may be as much as 25 times greater than otherwise; no transverse beam stacking is necessary; the general principle is already proven through charge exchange injection.

Reference

1. D. W. Turner, Molecular Photoelectron Spectroscopy (Wiley, New York, 1970).

TABLE I. Typical Parameters for Laser and Flashlamp Systems. MKS Units

Symbol	Definition	Laser	Flashlamp
I	ion beam current	.05	.05
E_t	energy deposited	10^7	10^7
β	v/c	.8	.8
ν	microexplosion rep. rate	5	5
E_d	dissociation energy per ion	$2.85 \cdot 10^{-19}$	$.575 \cdot 10^{-18}$
L	length of beam pulse	$.44 \cdot 10^4$	$.44 \cdot 10^4$
s	transverse stacking avoided	1000	1000
r	no. of recirculations	50	
a	ion beam radius		$.5 \cdot 10^{-2}$
σ	dissociation cross section	10^{-21}	10^{-21}
ε	ion beam emittance	$.6 \cdot 10^{-4}$	
f	no. of e-foldings of dissociation	5	5
E_ℓ	light energy per pulse	63.	$.4 \cdot 10^6$
P	instantaneous light power	$.63 \cdot 10^5$	$2.0 \cdot 10^9$
S	power supply with losses	$.63 \cdot 10^7$	$2.0 \cdot 10^{10}$



RUBY-LASER DISSOCIATION GEOMETRY AND RECIRCULATION

FIGURE 1.